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# Assessing the coupling between surface albedo derived from MODIS and the fraction of diffuse skylight over spatially-characterized landscapes

Miguel O. Román [a,b,*], Crystal B. Schaaf [a], Philip Lewis [c], Feng Gao [b,d], Gail P. Anderson [e,f], Jeffrey L. Privette [g], Alan H. Strahler [a], Curtis E. Woodcock [a], Michael Barnsley [h]

[a] Department of Geography and Environment, Boston University, Boston, MA, USA
[b] Hydrospheric and Biospheric Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA
[c] Department of Geography, University College London, London, UK
[d] Earth Resources Technology, Inc., Annapolis Junction, MD, USA
[e] Global Monitoring Division, Earth System Research Laboratory, NOAA, Boulder, CO, USA
[f] Space Vehicles Directorate, Air Force Research Laboratory, Hanscom Air Force Base, MA, USA
[g] NOAA National Climatic Data Center, Asheville, NC, USA
[h] Department of Geography, University of Wales Swansea, Swansea, UK

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ABSTRACT

In this effort, the MODerate Resolution Imaging Spectroradiometer (MODIS) (Collection V005) Bidirectional Reflectance Distribution Function (BRDF)/Albedo algorithm is used to retrieve instantaneous surface albedo at a point in time and under specific atmospheric conditions. These retrievals are then used to study the role that the fraction of diffuse skylight plays under realistic scenarios of anisotropic diffuse illumination and multiple scattering between the surface and atmosphere. Simulations of the sky radiance using the MODTRAN®5.1 radiative transfer model were performed under different aerosol optical properties, illumination conditions, and surface characteristics to describe these effects on surface albedo retrievals from MODIS. This technique was examined using a validation scheme over four measurement sites with varied aerosol levels and landscapes, ranging from croplands to tundra ecosystems, and over extended time periods. Furthermore, a series of geostatistical analyses were performed to examine the types of spatial patterns observed at each measurement site. In particular, Enhanced Thematic Mapper Plus (ETM+) retrievals of surface albedo were acquired to analyze the change in variogram model parameters as a function of increased window-size. Results were then used to assess the degree to which a given point measurement is able to capture the intrinsic variability at the scale of MODIS observations. Assessments of MODIS instantaneous albedos that account for anisotropic multiple scattering, over snow-free and snow-covered lands and at all diurnal solar zenith angles, show a slight improvement over the albedo formulations that treat the downwelling diffuse radiation as isotropic. Comparisons with field measurements show biases improving by 0.004–0.013 absolute units (root-mean-squared error) or 0.1%–2.0% relative error.

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## 1. Introduction

Surface albedo describes the ratio of radiant energy scattered upward and away from the surface in all directions to the downwelling irradiance incident upon the surface. It is a key variable in regional and global radiation schemes, since it largely controls the amount of solar energy absorbed at the surface. Surface albedo is dependent on the Bidirectional Reflectance Distribution Function (BRDF), which describes the anisotropic reflectance of natural surfaces. Both surface albedo and the BRDF are determined by land surface structure, which influences the BRDF, for instance, by shadow casting, mutual view shadowing, and the spatial distribution of vegetation elements; and by surface optical characteristics, which determine the BRDF, for example, through vegetation–soil contrasts and the optical attributes of leaf scattering elements and the canopy reflectance. The spatial and temporal distribution of land surface properties, as seen in BRDF features, consequently reveal a variety of natural and human influences on the surface that are of interest to global change research (Lucht et al., 2000). As such, the accurate specification of satellite-derived albedos is important to earth system modeling efforts. Regional surface albedos with an absolute accuracy of 0.02–0.05 units (Henderson-Sellers & Wilson, 1983; Sellers et al., 1995) for snow-free and snow-covered land are required by climate, biogeochemical, hydrological, and weather forecast models at a diverse range of spatial (from 10s of meters to 5–30 km) and temporal (from daily to monthly) scales. Estimating albedos at intra-daily scales

* Corresponding author. Tel.: +1 301 614 5498; fax: +1 301 614 5269.
*E-mail address:* Miguel.O.Roman@nasa.gov (M.O. Román).

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also influences the accuracy of daily mean values of albedo. For instance a lack of consideration of the diurnal cycle of surface albedo yields an absolute error on the daily mean value of up to ±0.03 units, corresponding to 15% in relative terms (Grant et al., 2000). Similarly, Kimes et al. (1987) reported an 18% relative bias on the daily mean value of reflected solar irradiance.

Satellite remote sensing offers the only realistic means of monitoring surface albedo in a continental or global sense by providing spatially variable and temporally dynamic observations. With the launch of a number of polar orbiting sensors over the past decade, including MODIS, MISR, CERES, MERIS, and Parasol-POLDER, several global land surface albedo products are now being routinely produced. These datasets rely on multiple clear sky observations to characterize surface reflectance properties and must therefore contend with issues of cloud-clearing, snow detection, and aerosol correction as well as sensor-specific matters of view angle, spatial footprint, gridding, repeat cycles, and narrowband- to broadband conversion. These challenges have been successfully overcome in albedo-retrieving algorithms such as those of MODIS (Lucht et al., 2000; Schaaf et al., 2002, 2008; Wanner et al., 1997), MISR (Martonchik et al., 1998), and POLDER (Bacour & Breon, 2005; Buriez et al., 2007; Hautecoeur & Leroy, 1998; Maignan et al., 2004). Among these products, the MODIS V005 BRDF/albedo product provides intrinsic biophysical parameters of the surface, including surface reflectance anisotropy (BRDF model parameters), directional–hemispherical reflectance, and bihemispherical reflectance under isotropic illumination. These quantities are retrieved in seven narrow spectral bands between 0.4 and 2.4 μm as well as three broad bands encompassing the full solar range (0.3–5.0 μm) as well as the visible (0.3–0.7 μm) and shortwave infrared (0.7–5.0 μm) portions of that range.

To compare MODIS-derived surface albedo parameters with field-measured albedos, the MODIS intrinsic albedo quantities are normally combined as a simple weighted sum using the fractions of beam and diffuse illumination calculated for the observed optical depth and an appropriate atmospheric model using a Lambertian surface with a reflectance typical of the surface type (Lewis & Barnsley, 1994; Lucht et al., 2000). This formulation assumes that the directional distribution of sky radiance is unimportant since albedo involves an integration over illumination angles, and that albedo enhancement due to multiple interactions between the ground and atmosphere can be approximated within the definition of the diffuse proportion of illumination. This can lead to errors of a few percentages that have heretofore been ignored. Lewis and Barnsley (1994) noted that errors can increase under these assumptions at high solar zenith angles (SZA) and for atmospheres with high concentrations of aerosols. Pinty et al. (2005), have suggested that such errors can be as high as 10% (relative bias) under extremely turbid atmospheres and over strongly anisotropic surfaces. It is important to note that the MODIS V005 BRDF/albedo product is, nevertheless, a clear sky product. Thus, the algorithm was not designed to be specifically robust against conditions of increased haziness and at SZA>75°. Further, although there have been efforts to make sure that the underlying BRDF models operate well even at these higher zenith angles (Gao et al., 2001) and by other authors for the hotspot region (Maignan et al., 2004), the model parameters and hence the BRDF prediction relies on fitting to some limited set of satellite observations giving rise to uncertainty in the surface reflectance involved in any integral to albedo. Although earth system modelers have embraced the MODIS products and used them to refine their surface radiation parameterizations (Lawrence & Chase, 2007; Oleson et al., 2003; Wang et al., 2004; Zhou et al., 2003), they acknowledge that true land–atmosphere coupled albedos are also needed to gain a better understanding of the earth surface processes that they describe.

This paper addresses the specific role of anisotropic sky radiance and multiple scattering when using MODIS surface reflectance anisotropy products to reconstruct surface albedo at a point in time and under specific atmospheric conditions. A new method has been implemented to estimate instantaneous surface albedo, including the multiple scattering effects and the directional distribution of sky radiance. This method has been tested over a set of simulations using the MODTRAN®5.1 radiative transfer model (Berk et al., 2004). A number of test cases were also evaluated to determine robustness during periods of increased haziness. Results were then assessed against coincident field measurements over four field stations with landscapes ranging from croplands to tundra ecosystems and varied aerosol levels, to test the ability of the MODIS surface reflectance anisotropy data to capture the daily variability of surface albedo. Ground observations of surface albedo were obtained on an hourly basis during 3 to 5 year sampling periods using concurrent measurements of aerosol optical properties obtained by AErosol RObotic NETwork (AERONET) sunphotometers (Holben et al., 2001).

A spatial characterization of the MODIS V005 BRDF/albedo product was performed using 30 m Enhanced Thematic Mapper Plus (ETM+) albedo subsets as an intermediate between the satellite and point (tower) measurements. Although spatial scaling effects will always play a role in comparisons between coarse resolution satellite retrievals and fine resolution tower measurements, application of a geostatistical characterization of each site was also performed to indicate which measurement sites are most influenced by spatial scaling effects (in addition to any anisotropic effects). This approach improves the development and comparison of the proposed set of inversion techniques to estimate actual surface albedo from MODIS data.

## 2. Background

### 2.1. BRDF, albedo, and other definitions

The following is a summary of symbols and variables of interest related to BRDF and albedo, and remote sensing measurements. The definitions are linked to nomenclatures proposed by Nicodemus (1977) and reviewed in Liang (2004), Martonchik et al. (2000), and Schaepman-Strub et al. (2006):

Spectral and directional quantities:

$$\vartheta = \text{zenith angle} \tag{1}$$

$$\phi = \text{azimuth angle} \tag{2}$$

$$\Omega_s = \text{solar geometry} \tag{3}$$

$$\Omega_v = \text{viewing geometry} \tag{4}$$

$$\Omega_i = \text{incident geometry} \tag{5}$$

$$\lambda = \text{wavelength} \tag{6}$$

$$\Lambda = \text{waveband } \Lambda \text{ of width } \Delta\lambda \tag{7}$$

Atmospheric quantities:

$$L_{\lambda}\downarrow(\Omega_i) = \text{downwelling spectral radiance (at the ground) in direction } \Omega_i \tag{8}$$

$$L_{0\lambda}\downarrow(\Omega_i) = \text{downwelling spectral radiance at the bottom of the atmosphere over a totally absorbing lower boundary} \tag{9}$$

$$L_{0\lambda,Iso}\downarrow(\Omega_s) = L_{0\lambda}\downarrow(\Omega_i) \text{ under assumptions of isotropic diffuse illumination} \tag{10}$$

$$L_{0\lambda}(\Omega_i) = \text{downwelling diffusely-transmitted radiance at the bottom of the atmosphere for a totally absorbing lower boundary} \tag{11}$$